Report of the Global Synthesis and Observations Panel
July 2014

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1 GSOP Achievements

1.1 ACHIEVEMENTS

1.1.1 Promoting and evaluating observing systems and defining observational requirements

The CLIVAR GSOP initially grew out of and built on the accomplishments of an earlier panel, the CLIVAR Upper Ocean Panel (UOP). The UOP was central to the transition from the TOGA/WOCE observing system of the early 1990s, and (along with GODAE) to the creation of systematic global ocean observing systems including the Argo Program. The UOP and OOPC were co-convenors of the OceanObs99 Conference, upon which today's community consensus on global ocean observations rests. In particular OceanSITES has its origins in that conference. GSOP has continued this global role of advocacy, recognizing that with an initial observing system in place, synthesis activities including statistical analyses and ocean data assimilation modeling take on major roles in evaluating and evolving the observing system. The observing systems represented in GSOP provide both data that enter the data assimilation products (such as ARGO) and data which are better suited for validation and evaluation of the models/products (such as OceanSITES). Today's community consensus, updated by OceanObs09 and similar activities in which GSOP continues to play central roles, underlines the high societal value of ocean/climate research and of operational applications (reanalysis and initialization of forecast models) of sustained global observations. While the CLIVAR basin panels have served to design the regionally specific observational elements, GSOP's role is to weigh the balance, consistency, and completeness across these regional components. GSOP, along with OOPC, is the voice of basic research in observing system advocacy, and as long as basic research is a strong (or the dominant) application of the observing system, this voice will continue to be an essential one."

In the past decade, GSOP has been working closely with the Global Ocean Data Assimilation Experiment (GODAE) and its follow-on GODAE OceanView to demonstrate the value of ocean observing systems (both satellite and in-situ) in ocean state estimation and in initializing seasonal-to-interannual climate prediction through Observing System Experiment (OSE) and Observing System Simulation Experiment (OSSE). A joint workshop took place in November 2007 in Paris, France, with a follow-up workshop in September 2011 in Santa Cruz, California. The outcome of the workshop provided strong advocacy for the value of various observing systems such as multiple altimeters, Argo floats, and tropical mooring systems. In January 2014, the GSOP community also provided strong advocacy for the TOGA-TAO system in estimating the state of the tropical Pacific Ocean and ENSO prediction.

GSOP has also been working closely with the Ocean Observation Panel for

Climate (OOPC) to define observational requirements for Essential Ocean Variables (ECVs) for the Global Climate Observing System (GCOS). GSOP has provided valuable input to the GCOS in terms of spatial and temporal sampling and accuracy requirements for phenomena on different climate time scales for temperature and salinity. These contributions will be used for the upcoming update of observational requirements and observing strategy by GCOS (in 2016).

1.1.2 GO-SHIP

GSOP has played a major role in the development oft he Global Ocean Ship-based Hydrographic Program (GO-SHIP) Program. GO-SHIP brings together scientists with interests in physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems, and other users and collectors of hydrographic data to develop a globally coordinated network of sustained hydrographic sections as part of the global ocean/climate observing system. Global hydrographic surveys have been carried out approximately every decade since the 1960s through research programs such as IIOE, GEOSECS, WOCE / JGOFS, and CLIVAR. In 2009 the Global Ocean Ship-based Hydrographic Program (GO-SHIP) was established as part of the Global Ocean Observing System under the WCRP to provide international coordination and scientific oversight of the decadal global ocean survey. GO-SHIP aims to develop a globally coordinated network of sustained hydrographic sections as part of the global ocean/climate observing system including physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems. GO-SHIP provides approximately decadal resolution of the changes in inventories of heat, freshwater, carbon, oxygen, nutrients and transient tracers, covering the ocean basins from coast to coast and full depth (top to bottom) ,with global measurements of the highest required accuracy to detect these changes.

The GO-SHIP principal scientific objectives are: (1) understanding and documenting the large-scale ocean water property distributions, their changes, and drivers of those changes, and (2) addressing questions of how a future ocean that will increase in dissolved inorganic carbon, become more acidic and more stratified, and experience changes in circulation and ventilation processes due to global warming, altered water cycle and sea-ice will interact with natural ocean variability. The first decadal survey was the more extensive World Ocean Circulation Experiment (WOCE) survey of the 1990s. The continuing surveys are a subset of the WOCE survey, designed to provide sparse sampling of each major ocean basin for comparison with the WOCE baseline.

1. Network Status – measured against requirements with details of variables

- 2003-2012 Decadal Survey

The second decadal survey was completed. Almost all sections were occupied within the 2003-2012 period. The decadal survey included once-per-decade sections in all ocean basins and higher frequency sections in the Southern Ocean (Drake Passage and South of Australia and Africa) and high latitude North Atlantic Ocean and Arctic Ocean. The northern Indian Ocean sections (I01W and E, I02 and I07N) were not completed due to security risks. These sections still remain part of the global survey, although uncertainty remains about when they will next be completed.

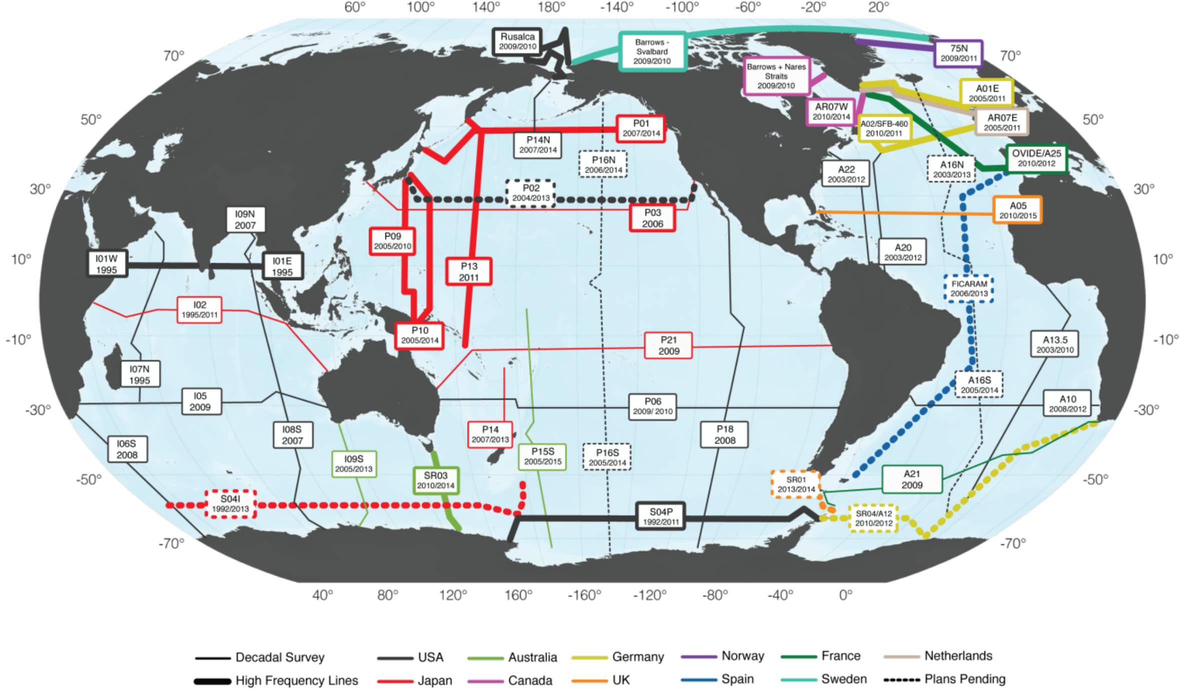

Figure 1: GO-SHIP sections most recently completed and planned occupations.

Most data are available at CDIAC (carbon) and CCHDO (CTD and most bottle data). We are continuing to contact PIs to ensure all data are available at the data centres. The time-series of ocean properties derived from the global decadal survey provided significant insight into the importance of the ocean in climate and climate variability. For example, these data have documented substantial changes in the oceanic inorganic carbon content, driven by both the uptake of anthropogenic CO_2 and natural variability; evidence of large-scale changes in oceanic oxygen concentrations; near global-scale warming of abyssal waters of Antarctic origin, and freshening of these waters in deep basins adjacent to Antarctica; intensification of the global hydrological cycle; reduction in the lower limb of the meridional overturning circulation; and estimates of water mass formation rate. GO-SHIP is also now including the more regional MEDSHIP (not shown in Figure 1), through Toste Tanhua. MEDSHIP is a consortium of countries involved in developing a long-term ship-based sampling of the Mediterranean Sea.

- 2012-2023 Decadal survey

The 3rd decadal survey has begun. We have complete sections in the Atlantic (A20 and A22 occupied in 2012; A16N now being occupied in 2013) and North Pacific (P02 occupied in 2013). The tables below provide information on planned and or funding status of the sections. We are actively gathering information on the status of national plans to update these tables (see http://www.go-ship.org/CruisePlans.html). To this end, we have developed a document to capture information on the parameters that will be collected on each voyage (see http://www.go-ship.org/Cruise-Notice.pdf). This form has been distributed to national representatives for completion.

1.1.3 Climate-standard subsurface ocean data quality control (IQuOD)

GSOP leads an internationally-coordinated effort for coordinated quality-control of Global Subsurface Ocean Climate Observations, the International Quality-Controlled Ocean Database (IQuOD) effort. An inaugural meeting organized by GSOP took placed in Hobart, Australia in June 2013 (http://www.clivar.org/organization/gsop/activities/clivar-gsop-coordinated-quality-control-global-subsurface-ocean-climate). An IQuOD Town Hall meeting took place during the 2014 Ocean Sciences meeting in Honolulu, Hawaii, USA in February 2014 (http://www.sgmeet.com/osm2014/viewagendadetail.asp?type=Workshops%20and%20Town%20Halls&Date=2/24/2014&start=12:45:00&end=21:30:00). The second IQuOD workshop too place in Washington DC, USA in June 2014 (http://www.iquod.org/). An IQuOD discussion session was held in the second meeting of the Joint IODE-JCOMM Steering Group for the Global Temperature-Salinity Profile Programme in Oostende, Belgium in June 2014 (http://www.iode.org/index.php?option=com_oe&task=viewEventRecord&eventID=1388).

1.1.4 Global ocean synthesis product evaluation

There is increasing demand for historical records of the ocean variability and change. For example, historical records of the ocean are needed as a reference for monitoring the current state of the climate, and also to initialize and validate long-range (e.g. seasonal and decadal) forecasts. Observations alone are often inadequate to generate the required estimate of the ocean variables and diagnostic quantities. Ocean model simulations can provide some insight on the ocean variability, but they are affected by errors in model formulation, initial states and forcing, and are not directly constrained by observations. Ocean reanalyses are the combination of ocean models, atmospheric forcing fluxes and ocean observations via data assimilation methods has the potential to provide more accurate information than observation-only or model-only estimations.

Ocean reanalyses are also referred to as ocean syntheses, which may be more appropriate since it reflects the process of objective synthesis of information from different sources. The designation *reanalysis* is not so intuitive, but mirrors the equivalent convention used for the more consolidated activities in the historical reconstruction of the atmosphere, and it has been adopted here.

The production of ocean reanalyses (hereafter referred to as ORAs) is now an established activity in several international research and operational centres. ORAs are revisited every so often, and new ‘vintages’ are produced at intervals of about five years, as improvements in ocean models, data assimilation methods, forcing fluxes or ocean observations become available.

In spite of the continuous improvements in methodology, the robust estimation of the historical ocean state with reliable error bars is a major challenge. In addition to the estimation of the three-dimensional ocean state at a given time (the analysis problem), the estimation of the time evolution is also required from a reanalysis. The time evolution represented by an ORA will be sensitive to the temporal variations of the observing system, to the errors of the ocean model, atmospheric fluxes and assimilation system, which are often flow-dependent, and not easy to estimate[6]. A crude but pragmatic way of estimating the current uncertainty in our ability to measure key ocean variables is to carry out an intercomparison of ORAs in a multi-reanalysis ensemble approach.

The First Phase of Global Ocean Reanalysis Intercomparison (2006-2009)

The performance of the previous vintage of ocean reanalysis (produced around 2006) was the topic of the first intercomparison project, led by Detleft Stammer, with the participation of all the existing ocean reanalyses at the time (Stammer et al 2010, Lee et al 2009, among others). This first intercomparison provided key material for the OceanObs09 conference by highlighting the potential of the ocean data assimilation in the exploitation of ocean observations for societal applications (climate monitoring, initialization of seasonal and decadal forecasts, among others). The intercomparison also provided a way of evaluating the uncertainty in the estimation of the ocean state, and attempted to investigate the source of uncertainty (observations, model, data assimilation or forcing fluxes). For instance, the signal-to-noise in the upper 300m was much larger for temperature than for salinity (figure 1, from Lee et al 2009) a manifestation of the lack of salinity observations. In some cases the dispersion among reanalyses increased was larger when using data assimilation than when using only ocean models, suggesting that the data assimilation method was partially responsible for the uncertainty in the estimates.

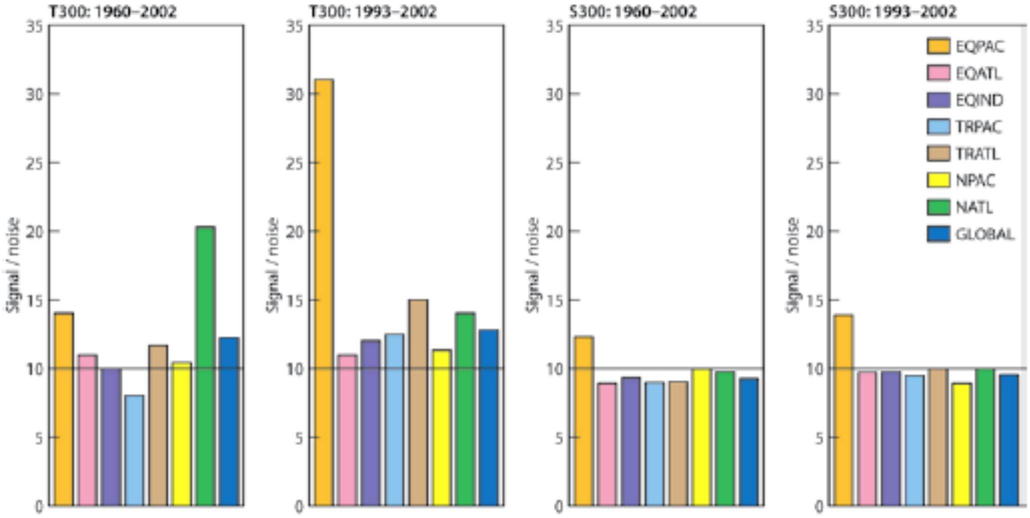

Fig 2. Signal-to-noise ratio in the time evolution of upper 300m temperature and salinity (T300 and S300 respectively) in different areas. The statistics were computed for the long period 1960-2002 and for a most recent period 1993-2002. From Lee et al 2009.

Resulting activities

The first coordinated intercomparison exercise spurred a variety of multi-system assessments. The multi-analysis ensemble approach has already been successfully used to study the ocean heat content (Xue et al 2012, Zhu et al 2011); to evaluate the Indonesian Throughflow using the INSTANT observations (Lee et al 2010); to create a robust index of the Atlantic Meridional Overturning Circulation that could be used for validation of decadal forecasts (Pohlmann et al 2013); to initialize seasonal (Zhu et al 2012, Zhu et al 2013) and decadal forecasts (Belluci et al 2013, Polhmann et al 2014).

Among the different applications of the ensemble of reanalyses, it is worth mentioning the applications for real time monitoring, which takes advantage of the reanalyses produced by operational centres to initialize seasonal forecasts. These products are continuously brought to quasi-real-time, with the model and data assimilation methodology kept fixed. The monitoring of the tropical Pacific conditions with a multi ocean reanalysis system (multi-ORA) advocated in OceanObs09 (Xue et al 2010) is now a reality, as it can be seen in the NCEP ocean monitoring pages (http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html)

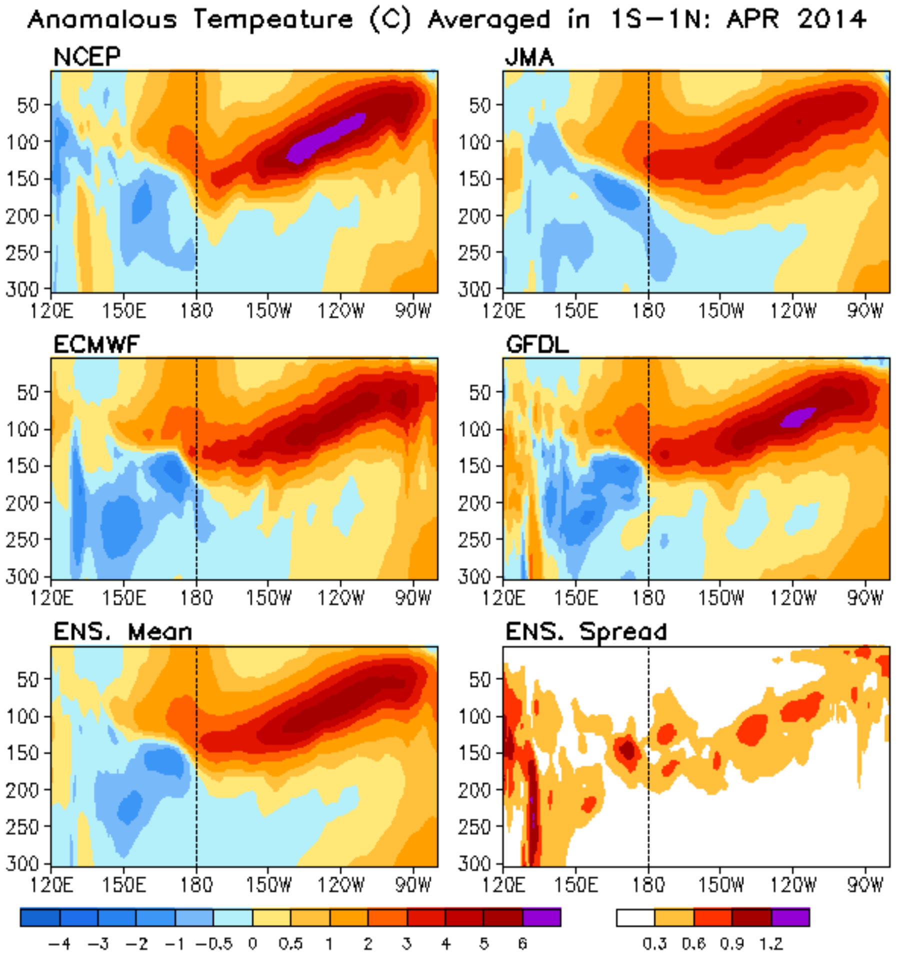

Figure 3: Real-time monitoring of ENSO using a multi-reanalyses approach. Shown are Equatorial cross-sections of temperature anomalies (respect 1981-2010 climatology) for April 2014, as represented by different ocean reanalyse, as well as the ensemble mean and spread. All the products show consistently the deepening of the thermocline in the Eastern Pacific announcing the onset of ENSO. From http://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html

The current Ocean Reanalysis Intercomparison Project (ORA-IP) (2012-2014)

A new vintage of ocean reanalyses has recently been generated, which has come about through the availability of new surface forcing fluxes (from new atmospheric reanalyses), improved quality-controlled ocean datasets, including important corrections to the observations (Lymann et al 2010, Wjiffels et al 2009) , as well as the steady improvement in the ocean models and data assimilation methods. There are lower resolution reanalyses (~1 degree horizontal resolution), spanning a long time period (typically 50 years), as well as higher resolution, “eddy permitting”, products (about ¼ of degree), which are available for shorter records (usually the altimeter period 1993-

onwards). The evaluation and exploitation of the most recent ocean reanalyses products is the subject of the current Ocean Reanalyses Intercomparison Project (ORA-IP), a coordinated community effort on the intercomparison of existing ORAs to exploit the existing information for a variety of purposes, namely i) quantifying uncertainty, ii) measuring progress in the quality of the reanalyses and iii) defining indices for ocean monitoring.

The joint workshop between GSOP and GODAE Ocean View communities (Santa Cruz 13-17 June 2011, Oke et al 2011) called for a community action on exploitation of the latest ORAs for real time climate monitoring and intercomparison.

Although the ultimate goal is the near realtime monitoring of the ocean through indices based on an ensemble of reanalyses, the first stage should be to complete an Ocean Reanalysis Intercomparison Project (ORA-IP). A viable proposal was put forward in Santa Cruz, based on the criteria of minimum effort. The following procedure was proposed:

A) Production centers: Operational and reanalysis centers were to provide relevant information (gridded fields of basic primary variables) in agreed formats and grids (where applicable), to enable the agreed intercomparison procedure to be carried out.

B) Processing centers: For intercomparison purposes each processing centre would take on a particular variable in which they have a strong interest and expertise. They would then be responsible for the intercomparison and eventually monitoring of that variable. They would process ensemble statistics based on the input from the individual production centres, and create relevant indices, metrics or graphics which could be directly compared.

Table1: List of ocean variables inter-compared, and responsible processing institution

Variable	
Steric Height	CMCC
Sea Level	Mercator Ocean
Ocean Heat Content	MetOffice
Depth of 20 degree Isotherm	Mercator Ocean
Mixed Layer Depth	MRI/JMA
Salinity	CAWCR
Surface fluxes and transports	University Reading
AMOC at 26N	University Reading
Sea Ice	Env Canada

Table 1 provides a list of the variables chosen for intercomparison. Table 2 lists the ORAs included in the study, and provides some details about the product name, associated institution, the ocean model, resolution[1] and coupling (default is uncoupled), assimilation and observations assimilated. The data assimilation column lists the observation types used for their estimation (T/S for temperature and salinity; SLA: altimeter-derived sea level anomalies; SSH: sea surface height -from tide gauges; SST: sea surface temperature, MDT: mean dynamic topography, SIC: sea-ice concentration), as well as assimilation techniques used for reanalysis: Optimal Interpolation (OI), Ensemble Kalman Filter (EnKF), Kalman Filters and Smoothers (KF-FS), Ensemble OI (EnOI), variational methods (3D-var and 4D-var). Some of the observational products also use statistical techniques such as Empirical Orthogonal Functions (EOFs). In addition to ORAs, the table also lists products named Obs-only (OO in what follows), meaning that they are observation-only products that do not include a dynamical ocean model. The OOs provide sea surface height (SSH) or its anomaly (SLA), and/or temperature and salinity (T/S) estimates, and sometimes 3D velocities (U,V), as in the case of ARMOR3D. The detailed description of the analysis systems joining ORA-IP and their differences is beyond the scope of this paper. However, more details about the products can be found in the references given in the table.

The production centres provided monthly-mean fields interpolated to the standard 1 × 1 degree latitude-longitude grid used by the World Ocean Atlas 2009[15] (WOA09), except for the transports, which were computed in the original grid and provided on the requested sections. For heat content, steric height and heat flux from assimilation increments, the values were provided as vertically integrated quantities from the surface to a number of fixed depths ranges: 0-100m; 0-300m; 0-700m; 0-1500m; 0-3000m; and 0-4000m.

The variety of ORAs can be exploited in assessing the strengths and weakness of the different systems, in the identification of gaps in the observing systems, and in the identification of robust quantities to use in climate monitoring, among others. The focus of the results presented is to identify the commonalities and differences among the variety of existing reanalyses. To this end, a multi-system ensemble approach is followed, where the signal and its associated uncertainty are measured by the ensemble mean (EM) and ensemble standard deviation (ESD) respectively.

Table 2: List of Ocean Reanalysis products entering the inter-comparison.

Product	**Institution**	**Configuration**	**Data Assim. Method**
ARMOR3D	CLS Guinehut et al 2012 Mulet et al 2012	1/3°Obs-only (T/S/SSH/U/V)	*OI (SLA/MDT/T/S/SST)*
CFSR	NOAA NCEP Saha et al 2012 Xue et al 2011	1/2° MOM4 coupled	*3DVAR (T/SST/SIC)*
C-GLORS05V3	CMCC Storto et al 2011	1/2° NEMO3.2	*3DVAR (SLA/T/S/SST/SIC)*

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[1] Even the low resolution models resolve the Equatorial Rossby Radius of deformation by including meridional grid refinement close to the Equator.

ECCO-NRT	JPL/NASA Fukimori 2002	1° MITgcm	*KF-KS (SLA/T)*
ECCO-v4	MIT/AER/JPL Wunsch and Heimbach 2013 Speer and Forget 2013	1° MITgcm	*4DVAR (SLA/SSH/T/S/SST)*
EN3 v2a	Met Office Hadley Center Ingleby and Huddelston 2007	1° Obs-only (T/S)	*OI (T/S)*
GECCO2	U. of Hamburg Köhl, A. 2014	1°x1/3° MITgcm	*4DVAR (SLA/T/S/MDT/SST)*
ECDA	GFDL/NOAA Zhang et al 2007 Chang et al 2013	1/3° MklceaOM4 coupled	*EnKF (T/S/SST)*
GloSea5	UK Met Office Waters et al 2014 Blockley et al 2013	1/4° NEMO3.2	*3DVAR (SLA/T/S/SST/SIC)*
MERRA Ocean	GSFC/NASA/GMAO	1/2° MOM4	*EnOI (SLA/T/S/SST/SIC)*
GODAS	NOAA NCEP Behringer 2007	1°x1/3° MOM3	*3DVAR (SST/T)*
G2V3	Mercator Océan	1/4° NEMO3.1	*KF+3DVAR (SLA/T/S/SST/SIC)*
K7-ODA(ESTOC)	JAMSTEC/RCGC Masuda et al 2010	1° MOM3	*4DVAR (SLA/T/S/SST)*
K7-CDA	JAMSTEC/CEIST Sugiura et al 2008	1° MOM3 coupled	*4DVAR (SLA/SST)*
LEGOS	LEGOS Meyssignac et al 2012	1/4° Obs-only (SL)	*OI+EOF (SLA/SSH)*
NODC	NODC/NOAA Levitus et al 2012	1° Obs-only (T/S)	*OI (T/S)*
PEODAS	CAWCR (BoM) Yin et al 2011	1°x2° MOM2	*EnKF (T/S/SST)*
ORAS4	ECMWF Balmaseda et al 2013 Mogensen et al 2012	1° NEMO3	*3DVAR (SLA/T/S/SST)*
MOVE-C	MRI/JMA Fujii et al 2009	1° MRI.COM2 coupled	*3DVAR (SLA/T/S/SST)*
MOVE-G2	MRI/JMA Toyoda et al 2013	0.5°x1° MRI.COM3	*3DVAR (SLA/T/S/SST)*
MOVE-CORE	MRI/JMA Tsujino et al 2011	0.5°x1° MRI.COM3	*3DVAR (T/S)*

	Danabasoglu et al 2013		
SODA	U. of Maryland and TAMU Carton and Giese 2008	1/4° POP2.1	*OI (T/S/SST)*
UR025.4	U. of Reading Haines et al 2012	1/4° NEMO3.2	*OI (SLA/T/S/SST/SIC)*
AVISO[44]	CLS	1/4° Obs-only (SSH/SLA)	*OI (SLA)*
SLCCI[45]	ESA Ablain et al 2013	1/4° Obs-only (SSH)	*OI (SSH)*

The first results of ORA-IP (Balmaseda et al 2014) identify those aspects that are robustly represented by the different products and those where there is a large level of discrepancy. Most of the reanalyses entering the intercomparison were state-of-the-art at the time they were produced (around 2010-11), in that they used the most advanced methodology (ocean models and data assimilation) and input data sets (observations and surface forcing) available at the time of production. The intercomparison has focused on a relatively small set of ocean variables, which were interpolated into a common horizontal grid, and for a limited set of vertical levels (when applicable), except for meridional transports, that were computed in the original grid. In this paper intercomparison results from the meridional transports are not presented, since they are still under development.

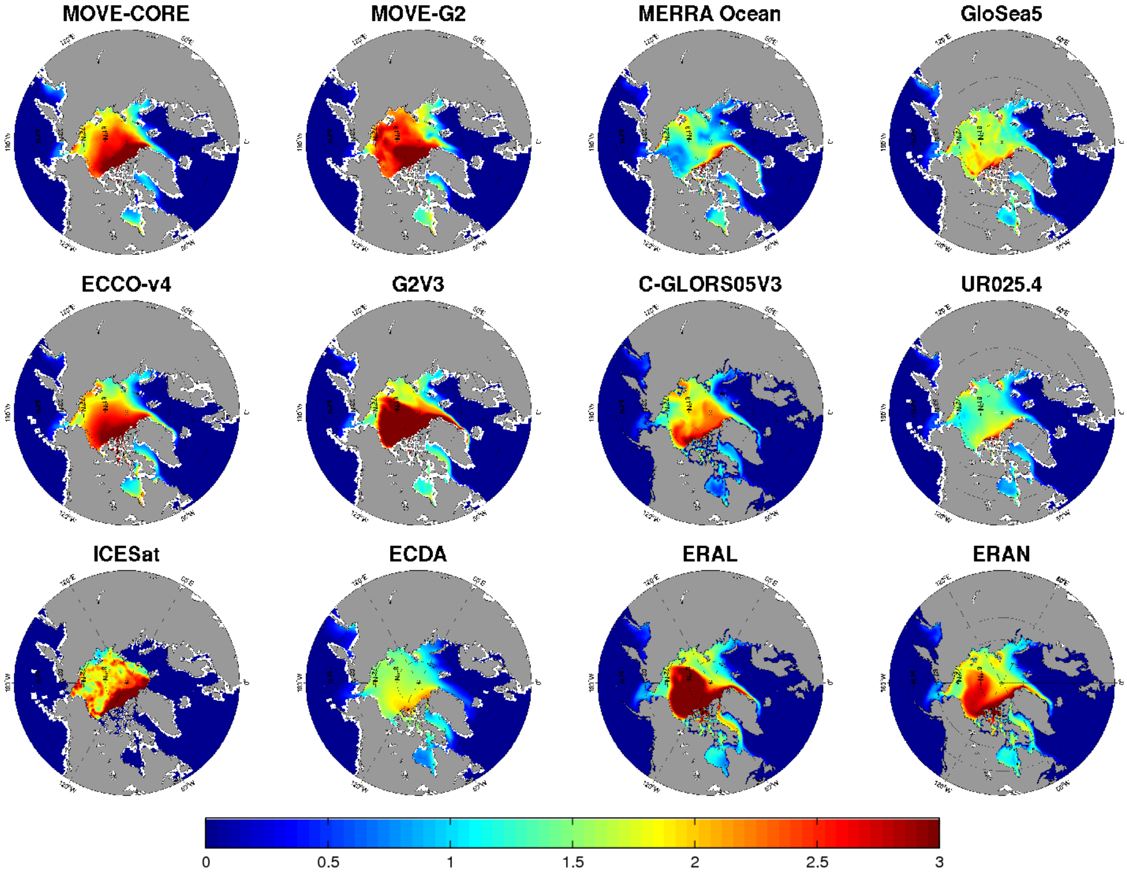

Fig. 4: Example of monthly mean sea ice thickness for the various ice-ocean reanalyses for March 2007. Also shown is a satellite estimate of sea ice thickness from ICESat (bottom left).

Where relevant (mixed layer, ocean heat content, steric height, sea level, salinity and thermocline depth) the ensemble mean of the ocean reanalyses was compared with observation only estimates, to see if the model-derived estimates show any systematic differences from the observation-only estimates. The ensemble spread is also used as a measure of the existing uncertainty. It is shown that the ensemble mean is usually a better estimation than any individual ocean reanalyses.

The uncertainty is large in poorly observed regions, such as the Southern Ocean, and in the deeper ocean, below the upper few hundred metres. Uncertainty is also large in the coastal areas, particularly along the path of the western boundary currents, where model errors and observation representativeness errors are large. These are also the areas of largest differences between obs-only and model-derived estimates. In salinity, the areas where the signal to noise ratio is larger than one is confined to the tropical western Pacific, probably because the interannual signal associated with ENSO is quite strong. The intercomparison of sea-ice showed a large uncertainty in the estimation of sea-ice thickness, which is largely unconstrained by the assimilation methods (figure 3). These results provide useful guidance for improvements of future observing systems.

The surface heat flux estimates from ocean reanalyses were compared with other products (figure 4), mostly based on atmospheric reanalyses. Although large uncertainty still exists, the ocean reanalyses global surface heat fluxes appear more balanced than the atmospheric-based products, especially when the contribution of the assimilation increments is taken into account.

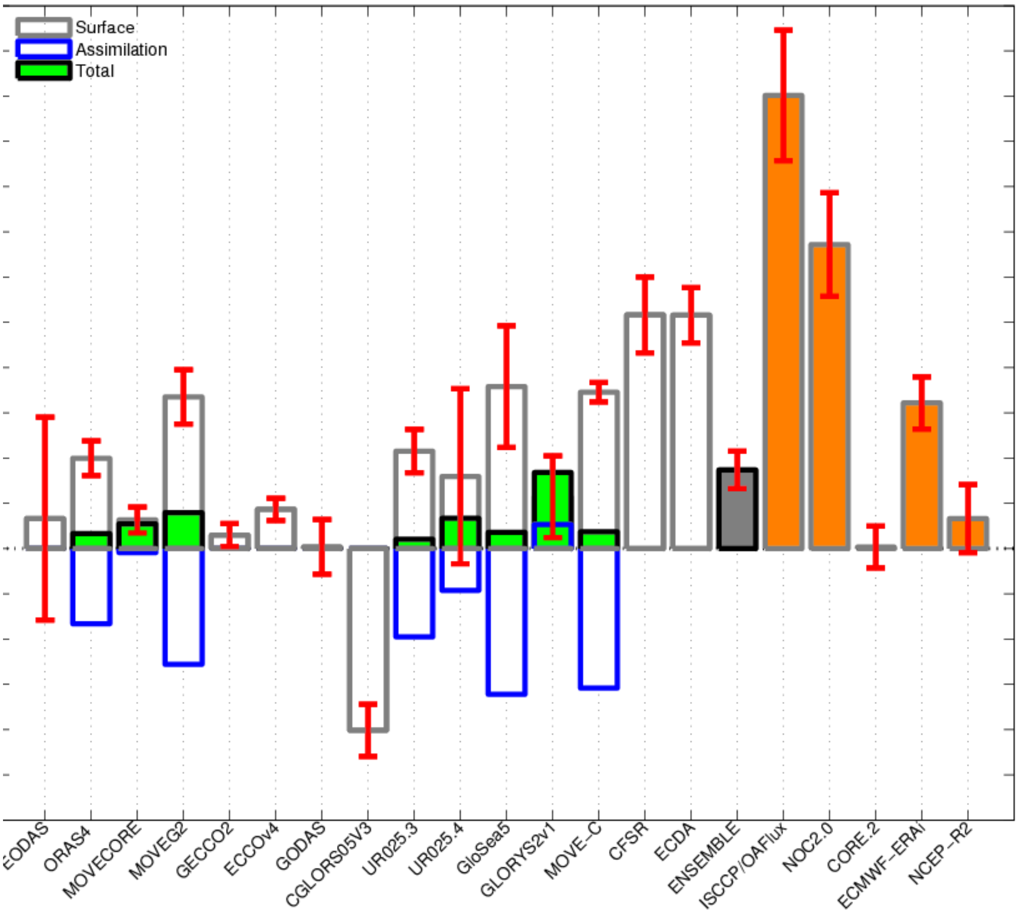

Fig 5: Time-mean global net "Surface" heat fluxes (grey bars) and their interannual standard deviations (red error bars) over the 17 years (1993 – 2009) spanned by all data sets. The
15-member ensemble of "Surface" flux products is also shown (dark grey bar), along with observation based on atmospheric reanalysis products to the right hand side (orange bars). Eight products also have "Assimilation" fluxes (blue bars) computed by integrating temperature increments from the surface down to the bottom, along with "Total" fluxes, i.e., "Surface" +"Assimilation" fluxes (green bars). Positive is heat flux into the ocean. Units are in Wm-2.

The ORA-IP activities are ongoing, and it is planned to disseminate the results to the wider climate community in a special issue in Climate Dynamics.

1.1.5 Utilization of ocean synthesis for initializing decadal forecasts

Partly through the initiative of CLIVAR, initialized decadal forecasts became firm part of the last CMIP5 effort and will continue to play a substantial role in climate resreach. Like seasonal forecast, the skill of decadal forecasts fundamentally depend on the proper initialization procedure of a coupled forecast system by the best possible estimate of the present-day climate state. Because the ocean caries a major fraction of the climate memory it is especially important to initialize those models by the present day ocean state. CLIVAR through GSOP pioneered the collection and quality controle of required global climate data set. Also through GSOP, CLVAR prioneered and organized on an international level the generation and use of ocean syntheses (often also referred to as ocean reanalyses) which through a combination of all available ocean data with a general circulation model lead to estimates of the chaning ocean. Respective ocean systemses exist now on a routine basis, covering 60 years and beyond and are being used to study the changing ocean and ocean transports as well as the interaction of the ocean with the overlaying atmosphere. A specific use of those ocean syntheses will remain the initialization of coupled forecast efforts.

The GSOP community has been engaging the decadal forecast community to use ocean reanalysis products to initialize decadal prediction. GSOP's effort has also led to emerging effort to use these products to test the impacts on decadal prediction (e.g., Pohlmann et al. 2009 and 2013, Belluci et al 2013, Polhmann et al 2014, Polkova et al., 2014).

To faciliate the related efforts, an ocean synthesis directory was established in University of Hamburg (http://icdc.zmaw.de/easy_init_ocean.html?&L=1) that contains the description of model configuration, data assimilated, and assimilation methods. The directory also contains some ocean reanalysis products that the decadal prediction community can obtain directly without having to retreive from individual data servers (some products do not have a dedicated data server).

1.1.6 Air-sea fluxes

1.1.6. Air-Sea Fluxes

Air-sea fluxes are central to climate research and consequently formed a key focus of the GSOP panel. A white paper on “Guidelines for Evaluation of Air-Sea Heat, Freshwater and Momentum Flux Datasets” (Josey and Smith 2006) was developed as a result of a recommendation made at an early GSOP meeting and revisited in discussion at the GSOP Flux workshop (Yu et al., 2012). It provides a basis for flux evaluation using global, regional, and local metrics as summarized below.

- Global: Metrics should include global mean Qnet at multidecadal timescales (which should be close to zero, i.e. within about +/- 2 Wm^{-2}), and corresponding means for individual flux components, along with characteristics of the statistical distributions of surface fluxes presented as climate maps and zonal means.

- **Regional:** Metrics should include the following two sets of computations.
a. Comparison of integrated net surface heat flux estimates for regions bound by reliable oceanographic heat transport estimates with the corresponding heat transport implied value.
b. Integrated surface flux estimates of individual flux components for selected regions with reasonably good coverage by in-situ observations and likely small impact of ocean dynamics and lateral advection, heat and freshwater budgets of selected semi-enclosed seas (e.g. the Mediterranean Sea).
The time series of these statistics is also highly desirable. Care needs to be taken here as conclusions reached for semi-enclosed seas may not be valid for the open ocean.

-**Local:** Metrics should include time series analysis along with probability and spectral characteristics of fluxes at surface flux reference buoy and OWS locations, together with measures of agreement with the reference observations.

It is important that all of the above metrics should be considered wherever possible.

Air-sea fluxes are recognised to be an important cross-cutting area within WCRP that link the interests of different programs including CLIVAR and GEWEX. The twin challenges of closing global ocean heat and freshwater budgets using models and observations, along with the importance of improving surface forcing functions for ocean and coupled climate modelling purposes, highlight the need for close collaboration between observation, modelling and synthesis communities. Under the auspices of WCRP/CLIVAR, US CLIVAR, NASA Physical Oceanography, and NOAA Ocean Climate Observations, the GSOP panel brought more than 60 international scientists from the air-sea flux and ocean synthesis communities together for a workshop at Woods Hole Oceanographic Institution (WHOI), USA, in November 2012 to address these challenges. This workshop aimed to (1) review the current state of surface fluxes of heat, freshwater and momentum obtained from ocean syntheses, atmospheric reanalyses, other observation based products, and coupled models, (2) discuss the gaps and current limitations in these products with particular reference to balancing ocean heat and freshwater budgets, and (3) develop recommendations and requirements for future global/regional synthesis activities. These areas of activity are relevant to the interests of the WOAP, WGSF and WCRP Data Council, specifically addressing recommendations in the Action Plan for WCRP Research Activities on Surface Fluxes (http://www.wcrpclimate.org/documents/woap_fluxes_report_01_2012.pdf).
Given the gaps in present-day knowledge and understanding, a consensus was reached during the workshop that achieving globally balanced energy and freshwater budgets is a long- term challenge, and should be broken down into incremental steps with achievable targets at each stage. Guided by the NASA and NOAA perspectives and objectives, the workshop discussions were directed toward seeking areas of collaborative research by;

(1) maximizing the use of existing observations made at the ocean surface and subsurface, *and*
(2) integrating regional budget analysis with direct pointwise comparison with in situ buoy/ship measurements.

The full workshop report can be found at (http://www.clivar.org/sites/default/files/ICPO189_WHOI_fluxes_workshop.pdf). Two key collaborative activities were recommended

1) A working group should be set up to develop strategy for regional heat/salt budget analysis and regional flux assessment using moored buoys and upper ocean observations from Argo

Rationale: Argo upper ocean heat/salt content observations can be regarded as a means of providing direct estimates of the total integrated air–sea fluxes of heat and freshwater averaged on some spatial and temporal scale. Argo observations, if estimates of uncertainty are included, should be capable of providing regional references for calibration of temporally integrated air–sea flux estimates in the same way that flux buoy and ship measurements have previously provided pointwise calibration information. These ocean data would greatly help to resolve the issues of regional biases and global imbalance that currently affect almost all flux products constructed from satellites, ships, and atmospheric reanalyses.

Caveats: Regional ocean heat budgets can provide information on the integrated heat flux but not the components. Advective convergence and divergence of heat may be important in the regional heat budgets, and if they cannot be sufficiently constrained these transport terms may dominate the error estimate on the regional air–sea flux budgets.

Selection of ocean regions for flux budget studies: Seek areas away from boundary currents where advective convergence is minimal, (e.g., enclosed and semi-enclosed basins such as the Mediterranean and the Red and Black seas). Seek areas that include within them one or more flux buoys, (e.g., the OceanSITES flux buoys or an ongoing field program such as SPURS, particularly buoys associated with process study data (e.g., STRATUS and PAPA). It was also recommended that satellite data and other in situ data (ships and drifters) be used to observe and/or assess the regional variability around the buoys. Analyze areas of particular interest for ocean processes (e.g., areas of water mass formation). Choose areas with the best Argo sampling over the longest period.

2) Comprehensive direct pointwise comparison of flux products and syntheses should be made with selected OceanSITES

Rationale: In situ air–sea measurements set the accuracy standard for gridded flux products.

Recommendations: It is recommended that these comparisons should be carried out for all global flux products, including atmospheric reanalyses, ocean syntheses, and parameterized flux products based on satellite data. The analysis of the heat and freshwater budgets from the different products around the calibration sites should yield insight into synthesis product consistency, distributions and scaling effects, and areas of common biases, as well as enable flux component comparisons.

The OceanSITES (full-flux) buoys at the following key climate locations are recommended (Fig.**)

- The Tropical Oceans (20°S-20°N, 9 buoys)

- 2 TAO buoys: (EQ, 110°W), (EQ, 165°E)
- 2 RAMA buoys: (EQ, 80°E), (15°N, 90°E)
- 3 PIRATA buoys: (EQ, 23°W), (10°S, 10°W), (15°N, 38°W)
- STRATUS (20°S, 85°W)
- Northwest Tropical Atlantic Station (NTAS) (15°N, 51°W)

- The subtropical region (20–40° north and south, 6 buoys)

- RAMA in the Indian Ocean southeast trade wind regime: (20°S, 100°E)
- WHOI Hawaii Ocean Time-series Station (WHOTS) in the north Pacific: (22.5°N, 158°W)
- Salinity Processes in the Upper Ocean Regional Study (SPURS) buoy: (24.5°N, 38°W)
- Kuroshio Extension Observatory (KEO) buoy: (32.4°N, 144.6°E)
- JAMSTEC Kuroshio Extension Observatory (JKEO): (38°N, 146.5°E)
- CLIVAR Mode Water Dynamic Experiment (CLIMODE) buoy: 38.5ºN, 65ºW

- Higher latitudes (poleward of 40° north and south, 2 buoys)

- Ocean Station PAPA: (50°N, 145°W)
- Southern Ocean Flux Station (SOFS): (47°S, 140°E)

Further recommendations from the workshop are listed below;

3) Ocean synthesis and reanalyses should separately archive components of the air-sea heat flux, i.e. Short and Longwave radiation, and sensible and latent heat fluxes, to facilitate comparisons with OceanSITES measurements.

4) Simple Web-based table with ftp links should be created to facilitate access to daily averaged and higher resolution net heat flux, the flux components, and meteorological state variables from moored buoys.

5) Reference station data (WMO type "84") should be withheld from reanalyses to allow independent assessment. WMO numbers of all data that are assimilated into NWP should be listed and made available.

6) The Seaflux website should be updated with recent data and metadata.

7) The Fluxnews Letter should be revived, to provide review of surface flux research, coordinated experiments, and relevant dataset publication.

8) The surface fluxes and synthesis communities should continue to enhance the interaction with relevant programs funded by different agencies (e.g., NASA and ESA Science Teams, NOAA program activities).

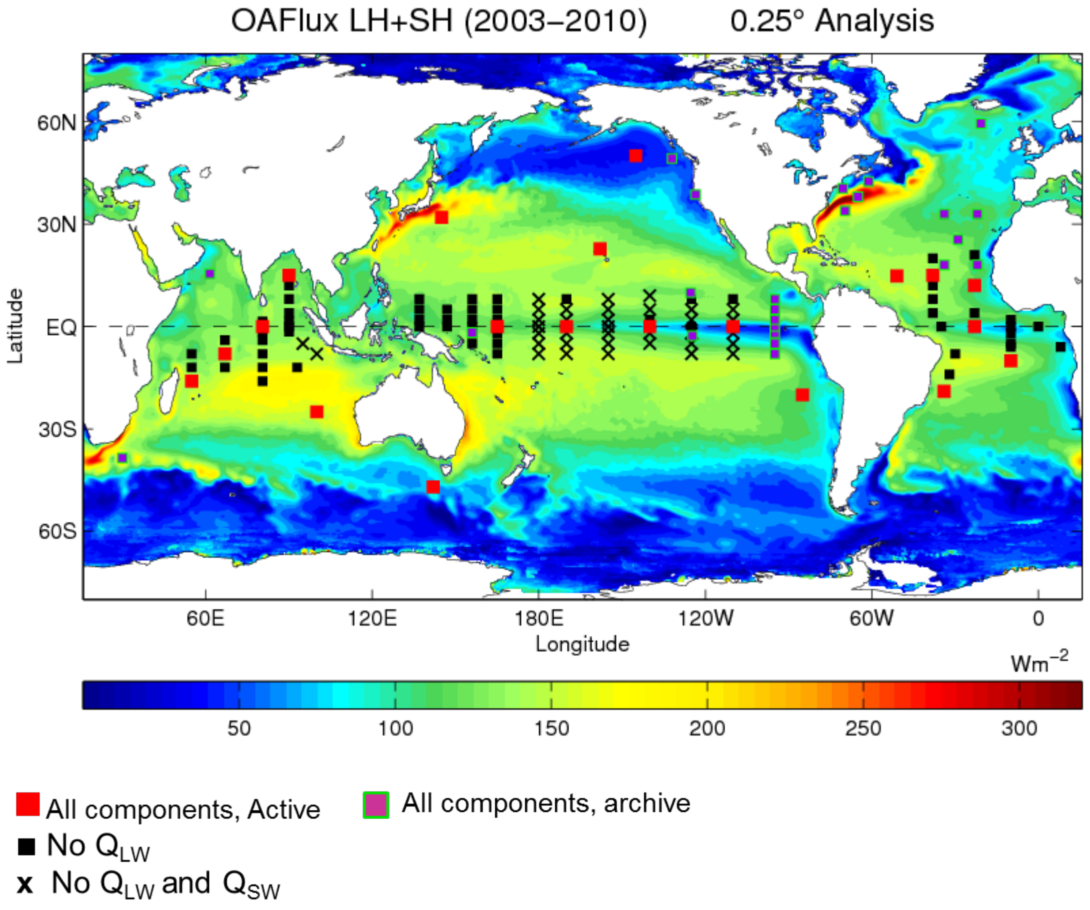

Fig. 6. Moored buoy locations over the global oceans superimposed onto the 0.25-degree OAFlux analysis of surface latent and sensible heat fluxes (colored background). Red squares denote full-flux buoy sites that provide all flux components (shortwave, longwave, latent and sensible heat fluxes, winds). Black squares denote the buoy sites that provide all flux components except longwave radiation. Crosses denote the sites that provide air–sea variables and winds for computing latent and sensible heat fluxes and wind stress only (from Li.san Yu).

1.1.7 Ocean heat content/energy balance and thermal expansion/sea level

Current and past members of the GSOP have been actively involved in intercomparsions of ocean heat content change using both statistical approaches (e.g. Lyman et al. 2010; Palmer et al. 2010; Abraham et al., 2013) and ocean reanalyses (e.g. Carton and Santorelli, 2008; Xue et al., 2012; Palmer et al, 2014), with the objective to understand and reduce sources of uncertainty in these estimates.

A major recent advance was the discovery of time-varying (warm) biases in historical expendable bathythermograph (XBT) data (Gouretski and Koltermann, 2007).

Attempts to account for, and remove, these XBT biases have resulted in a much improved comparison of climate model (CMIP) simulations with observational estimates for global upper-ocean (0-700m) heat uptake and thermosteric sea level rise, in terms of variability and multi-decadal trends (Domingues et al., 2008). This, in turn, has contributed to a better understanding of both energy and sea level budgets (e.g., Church et al., 2011; Hanna et al., 2013).

Spread among bias-corrected estimates of ocean heat content change (and hence, thermosteric sea level), however, remains large (e.g. Abraham et al., 2013; Church et al., 2013; Palmer et al., 2014). There are ongoing efforts to better quantify the origins of these discrepancies (Lyman et al., 2010; Boyer et al., pers comm.). One serious limitation in our ability to more properly account for instrumental biases, for example, is lack of necessary information to identify XBT probe types and manufacturer (Abraham et al., 2013). Without support for data archaeology activities, much of this crucial information (e.g., metadata and full-resolution data) cannot be recovered and used to refine corrections for systematic errors in the historical record

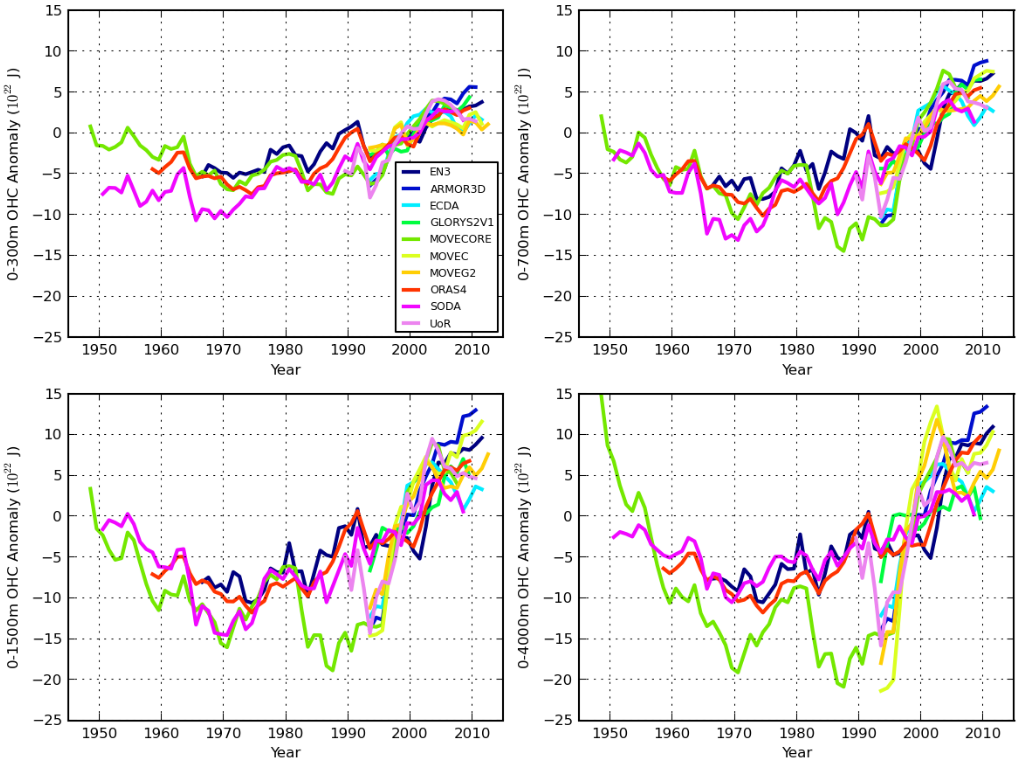

Figure 6: Time series of global ocean heat content anomaly, relative to a baseline period of 1993-2007. Note that SODA only includes grid boxes that span the full column and therefore will tend to underestimate OHC changes as the depth of integration increases. ARMOR3D and EN3 are statistical analyses and do not include a dynamic model component. Source: Palmer et al. (2014).

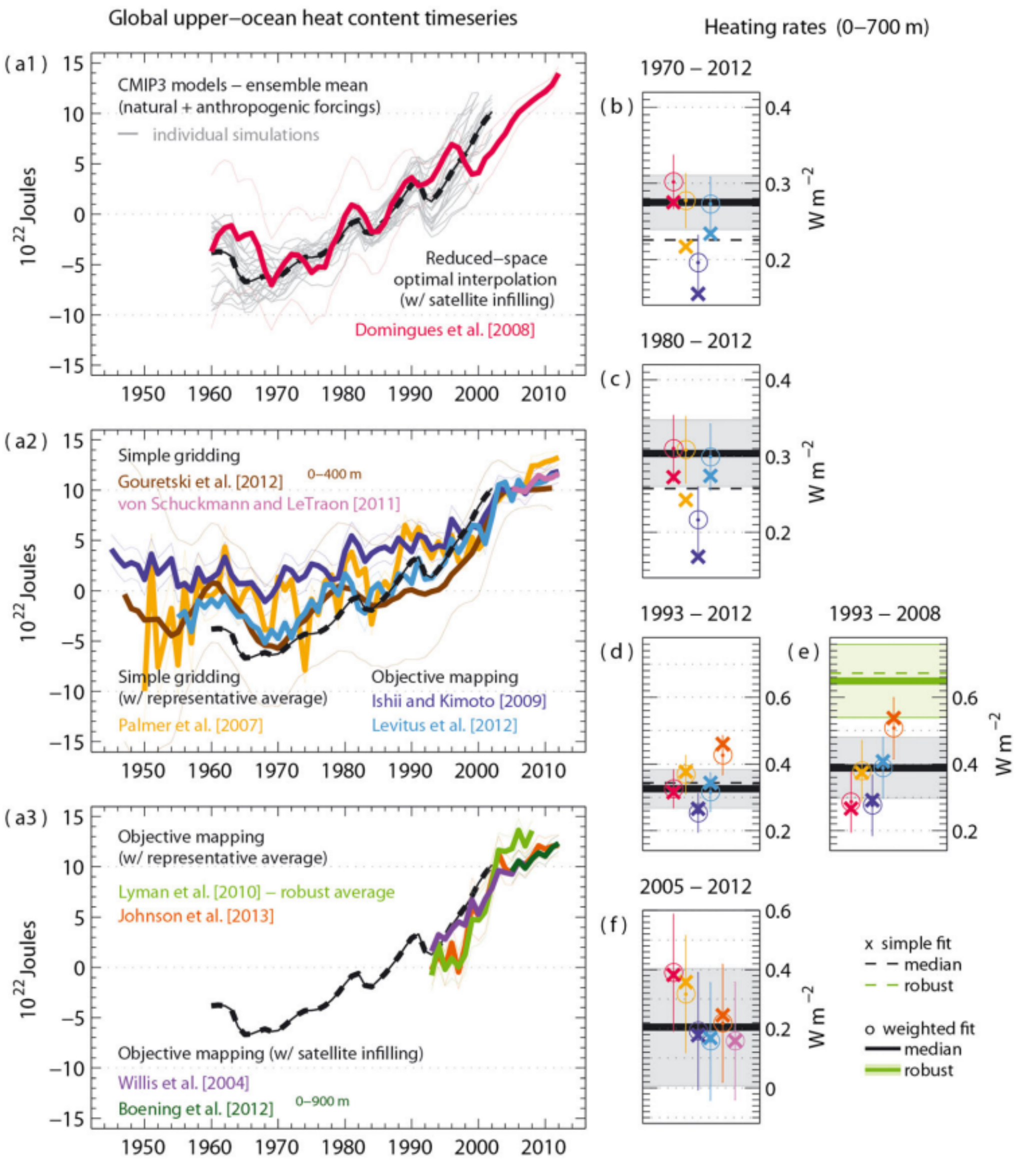

Figure 7: Time series of upper-ocean heat content change from a number of different statistical estimates (a1-3) and equivalent planetary heating rates for various periods (b-f). Source: Abraham et al. (2013).

http://www.argo.ucsd.edu/

Prior to 2005, the time at which the Argo float array achieved approximately global coverage (60°N-60°S), estimates of ocean heat content change are generally limited to the upper 700 m or so (e.g. above figure panels) and based on observations with sparse spatio-temporal coverage, particularly in the southern hemisphere (south of 30°S).

With the inception of the Argo array of autonomous profiling floats (http://www.argo.ucsd.edu/), our ability to monitor global and regional ocean heat content (steric sea level) variability and change significantly increased. In comparison to previous hydrographic data, Argo floats have better instrumental accuracy and sampling coverage. These floats return a profile of both temperature and salinity of the upper 2 km of the ocean with a 10-day repeat cycle. Caution, however, is still needed, as instrumental problems have been found and corrected to the extent possible (e.g., Willis et al., 2007; Barker et al., 2011). High-quality shipboard CTD programs are critical to maintain high accuracy and minimal systematic errors in the Argo array (and in other instrument types) (Freeland et al., 2010).

Besides maintaining the global array, Argo has the objective to extend the array further polewards (new development of Argo profilers able to measure in regions of ice cover), and into marginal seas. Due to a lack of temperature data polewards of 60° latitude, investigations are missing to understand the impact of these regions to changes in global ocean heat content. A consistency analysis of Argo global steric sea level to other independent observing systems, i.e. total sea level from altimetry and ocean mass from GRACE, has shown that low sampling in marginal seas can lead to a systematic bias in global estimates (von Schuckmann et al., 2014). The results are pointing out that the steric estimate from Argo (and hence, ocean heat content) is biased low as the current mapping methods are insufficient to recover the steric signal in marginal seas, in particular in the Tropical Asian Archipelago region.

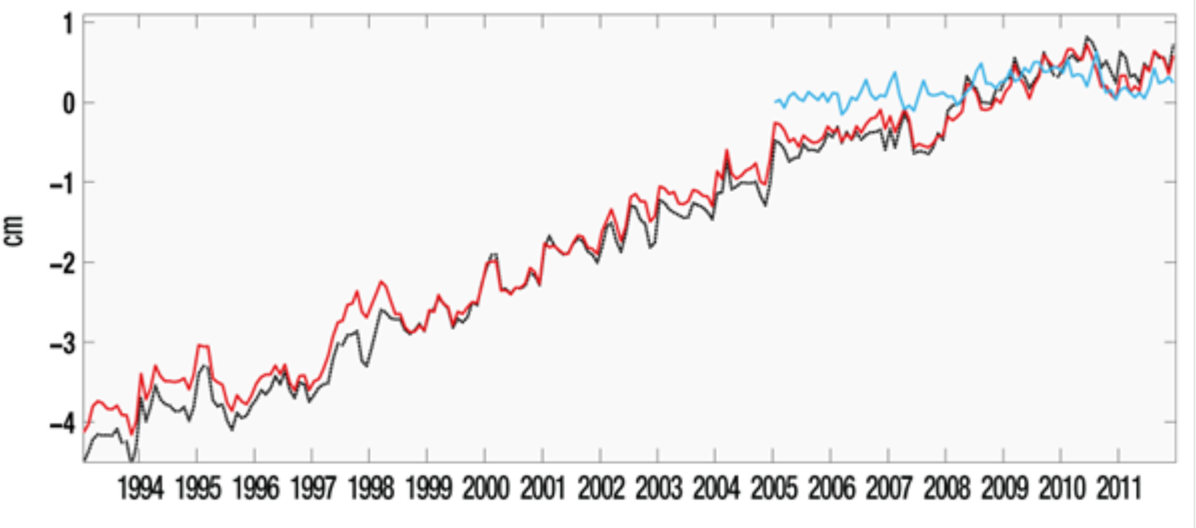

Figure 8: Global mean total (black) and steric (blue) sea level, together with global total sea level where data in the Tropical Asian Archipelago have been ignored (red). After von Schuckmann et al. (2014).

Another main objective for Argo is to extend the array into the deep ocean below 2000m depth for the global ocean (Garzoli et al., 2010; Purkey and Johnson, 2010). First technical developments and tests in the North Atlantic are under the way. This extension of the array is predominantly motivated by the role of the deep ocean in ocean heat uptake as analyses show that heat might be penetrating the deep ocean, beneath 700 meters, where there have not been reliable temperature measurements in the past (Trenberth and Fasullo, 2011, von Schuckmann et al., 2009, von Schuckmann and Le Traon, 2011). Previous estimates (e.g. Purkey and Johnson, 2010), found the deep ocean (below 1000 m) gaining heat at rates of less than 0.1 Wm^{-2} (95% confidence interval; global average). The most recent estimate of the ocean warming in 0–2000 m depth range of 0.39 W m^{-2} (per unit area of the World Ocean) from 1955 to 2010 emphasized the dominant role of the 700–2000 m depth range in the heat uptake (about one-third of the total warming) (Levitus et al., 2012). Hence, a deep observing array is urgently needed to quantify deep ocean heat uptake, as their estimation from other methods (e.g. intercomparison of Argo, Altimetry and gravimetry via the global sea level budget) is challenging as very high precision of the different observing systems is needed for such an approach (von Schuckmann et al., 2014).

One of the activities members of the GSOP have pursued is using climate model simulations to inform the need for improved observations of the full ocean depth (~4 km in the open ocean). Palmer et al. (2011) used pre-industrial control simulations to study Earth's energy budget and showed that global ocean heat content is the dominant term on decadal timescales. The authors found that there was considerable ocean content variability throughout the water column on decadal timescales, motivating the requirement for extending ocean observations deeper than Argo. A subsequent study using the available CMIP5 models (Palmer and McNeall, 2014) has shown diverse model behavior in the deep ocean, and that both internal variability in the top-of-atmosphere radiation budget and ocean heat redistribution are likely important in explaining observed global surface temperature variability.

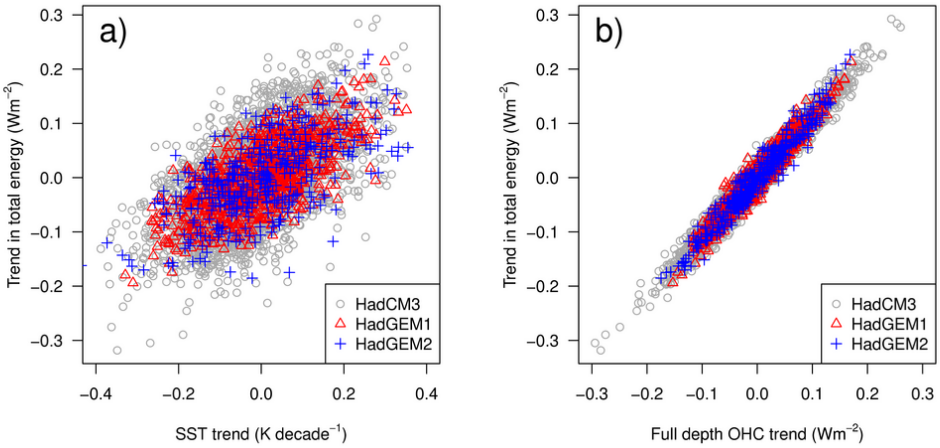

Figure 9: Plot of linear decadal trends in total energy (W m^{-2}) regressed against (a) decadal trends in globally averaged SST (K dec^{-1}); (b) decadal trends in full-depth OHC (W m^{-2}). Note that the trend in total energy is equivalent to the average top-of-atmosphere radiation balance (TOA) over the same period.

In the context of the global surface warming "hiatus" (Trenberth and Fasullo, 2013), members of the GSOP have used ocean reanalysis to investigate the role of ocean heat content variability (Balmaseda et al., 2013). They found an increased heat uptake in the ocean below 700 m, following the 1997/98 El Nino. Non-data-assimilation runs suggest a role for changes in the wind-driven upper circulation and associated sequestration of ocean heat, in support of recent observation and modeling studies (Kosaka and Xie, 2013; England et al., 2014; Meehl et al., 2011). The results of Balmaseda et al., (2013) are qualitatively supported by a number of independent ocean reanalyses (Palmer et al., 2014), including analyses that do not have a dynamic model component.

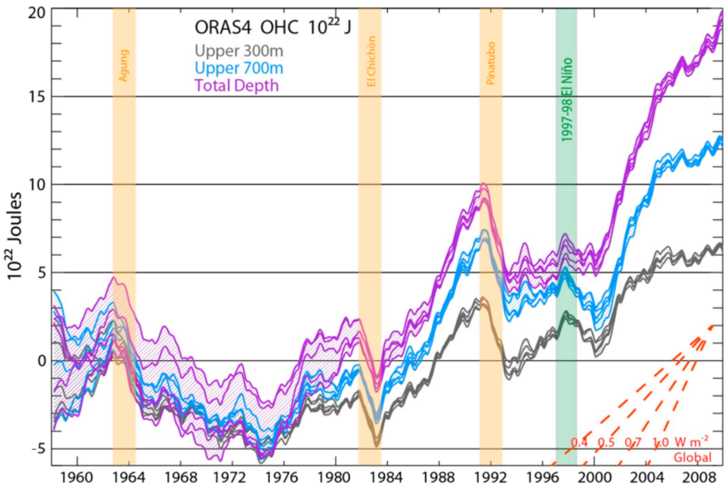

Figure 10: OHC integrated from 0 to 300 m (grey), 700 m (blue), and total depth (violet) from ORAS4, as represented by its 5 ensemble members. The time series show monthly anomalies smoothed with a 12 month running mean, with respect to the 1958- 1965 base period. Hatching extends over the range of the ensemble members and hence the spread gives a measure of the uncertainty as represented by ORAS4. Source: Balmaseda et al., (2013).

Variability in OHC and sea level are not only a consequence of human induced changes as they also respond to natural climate variability, producing noise in the record that hampers detection of the global warming signal and sea level rise (Cazenave et al., 2014). Separating year-to-year natural variability in sea level and OHC from the longer-term change likely related to global warming is a difficult target. Several decadal hiatus periods of the upper ocean warming associated with natural decadal and interannual variability, such as La Niña events, have been found in a model (Meehl et al., 2011). Recently, the 2001–2010 interannual variations of TOA radiation, OHC and global mean sea level have been associated with El Nino-Southern Oscillation (Loeb et al., 2012; Kosaka and Xie, 2013; Boubacar Dieng et al., 2014; Cazenave et al., 2014). A conclusion is that to describe the planetary heat balance during a hiatus period, it is necessary to integrate ocean heat content horizontally over the globe and vertically to the base of ENSO-related variations.

Climate is very much about exchange of energy in the Earth System, and in particular in the form of heat. Quantifying these exchanges, and in particular how much heat has been generated by human activities, and how it affects our climate system is one of the key challenges faced by the climate research community. Over the last decades, many studies based on both models and observations have been performed, leading to significant advances in our understanding of the energy exchanges (Hansen et al., 2005, 2011; Bindoff et al. 2007; Church et al., 2011; Trenberth and Fasullo, 2011; Bengtsson et al., 2012; Loeb et al., 2012; Stephens et al., 2012), while highlighting at the same time large uncertainties in the estimate of the energy flows. Developing the knowledge, and observational capability, necessary to "track" the energy flows through the climate system is therefore critical to better understand the relationships between climate forcing, response, variability and future changes (Allan, 2011).

In this context, CLIVAR has recently established a new research focus on "Consistency between Planetary Heat Balance and Ocean Heat Storage " [http://www.clivar.org/science/clivar-research-foci#six]. Several former and current GSOP members are involved in the formulation and establishment of this research focus. The main objective of the CLIVAR cross-cutting activity is to better understand the "role of the ocean in energy uptake " by analyzing consistency of heat budget components as seen by independent global observing systems, including (i) Earth Observation (EO) satellite data, (ii) in-situ measurements of ocean heat content storage changes, and (iii) Ocean reanalysis for heat transports and exchanges. Each of these independent approaches has its own advantages and drawbacks in terms of sampling capability and accuracy, leading to different estimates, and associated uncertainties of budget imbalance. Reconciling these different estimates to close the energy budget is a key emerging research topic in climate science.

The expected outcome:

1. Refinement of a scientific framework on consistency between planetary heat balance and ocean heat storage
2. Evaluation of existing data sets and information products and their consistency.
3. Recommendations on how to improve the observing systems and derived information products, assimilation methods, ocean and climate models and surface fluxes.
4. Contributing insights to related climate research topics such as anthropogenic climate change, seasonal climate prediction, decadal variability, predictability and prediction, as well as sea-level variability and change.

To address the EO component of the CLIVAR research opportunity, the GSOP community worked closely with the European Space Agency (ESA) is planning to start an activity on "Ocean Heat Flux" in partnership with CLIVAR within the framework of the ESA Support to Science Element (STSE) programme. After a scientific joint CLIVAR/ESA workshop in Reading in July 2013 (http://www.clivar.org/organization/gsop/activities/clivar-esa-scientific-consultation-workshop-earth-observation-measurement), a proposal has been established by the scientific community, which is currently under evaluation by ESA (Towards Improved Estimates of Ocean Heat Flux, TIE-OHF). This work is aiming to improve and calculate global long time series of ocean heat fluxes from satellite remotely sensed data.

In particular, a validation procedure is proposed in TIE-OHF based on the concept of “cages” (Bretherton et al., 1982) as discussed and highlighted during the GSOP workshop in Woodshole (Yu et al., 2012). Amongst others, the evaluation of a natural cage is proposed, i.e. the Mediterranean Sea. To support this activity, national funding from the french MISTRALS program (http://www.mistrals-home.org, ENVIMED call) could be established (March 2014, 2 year duration) aiming to strengthen the scientific community and analysis of the Mediterranean Sea heat and mass budgets, with particular focus on ocean heat content estimates.

In order to contribute to the refinement of a scientific framework on this research focus, an ISSI working group on “Consistency of Integrated Observing Systems monitoring the energy flows in the Earth System” has been recently established, and a first meeting will be hold during 11.-13. of June 2014 at ISSI in Bern, Switzerland.

2 Future plans and priority areas

2.1 IQuOD:International QUality-controlled Ocean Database (IQuOD)

Understanding climate variability and change is the most challenging application of subsurface ocean observations, as it demands the highest data quality, completeness and consistency. Particularly, long-term historical records are required to put modern changes in the context of past changes (e.g., long-term trends, acceleration), and to tease apart the influence of anthropogenic drivers from natural climate modes of variability (e.g., ENSO, NAO, IOD, SAM, PDO, AMO, etc).

Subsurface ocean temperature and salinity are two of the *Essential Climate Variables* which provide a direct window into understanding of changes in the Earth's planetary balance, hydrological cycle and sea level. Furthermore these subsurface ocean observations are widely used to either evaluate/constrain, initialize, or are assimilated into numerical models to investigate physical mechanisms and causes of past and current changes, and to predict/project future changes in our climate.

One of today’s big challenges, however, is the need to maximize the full potential of an irreplaceable collection of tens of millions of historical temperature (and salinity) profiles – collected since 1900s (or before) and worth tens of billions of dollars – to a vast range of climate-related research, applications and services of societal benefit.

Although there have been independent efforts over the past few decades by a number of research organisations, who have attempted to assemble, rescue and quality-control subsurface ocean profiles, the global historical database still contains a relatively large fraction of biased, duplicated and substandard quality (e.g., lack of original and full-resolution) data and metadata that can confound climate-related applications.

To overcome this difficult, a new internationally-coordinated effort – **IQuOD** – is being organized by the oceanography community (including ex- and current GSOP members), along with experts in data quality and management, and in consultation with end users (e.g., climate modellers, metrics panel) and the broader climate-related community.

Iniatially, the **overarching goal of the IQuOD initiative** is to produce and to freely distribute the highest quality, complete and consistent historical subsurface ocean temperature global database (to maximum extent), along with (intelligent) metadata and assigned uncertainties, and some downstream added-value products.

This goal will be achieved by developing and implementing an internationally-agreed framework. No individual group has the expertise/resources to complete the above task. International coordination/cooperation is essential to the success of the IQuOD initiative. Present IQuOD members include experts from various countries, for example: Argentina, Australia, Brazil, Canada, China, France, Germany, India, Japan, Mexico, Norway, Russia, Spain, South Africa, UK, USA.

By pooling expertise and resources into a single best practice community effort, the IQuOD initiative plans to achieve the best outcome over the shortest timeframe, at the same time to avoid duplication of human and infrastructure resources, particularly welcome in times of budget cuts. Although internationally-coordinated efforts exist for the ocean surface and atmosphere-ocean observations, no similar effort has been undertaken for the historical subsurface ocean observations to this date.

IQuOD plans to initially focus on temperature but plans to extend its efforts in the future to other subsurface ocean variables, such as salinity, oxygen and nutrients.

IQuOD expected outcomes include:

- Development/implementation of international standard practices for automated/manual quality control of historical (and modern) temperature data and provision of (intelligent) metadata and uncertainties. This involves agreement on best practices; open-source software development/ documentation/deployment; personnel training (capacity building); application of quality control procedures/audits.
- Template for future efforts: great community interest in improving the quality, completeness and consistency of the historical salinity observations and other ocean variables.
- Important data legacy (e.g., raw and interpolated products) and numerous downstream applications of the IQUOD dataset for Earth system/climate-related research and services of great societal benefit, including future CLIVAR (e.g., Section 2.4: Ocean Climate Indicators; Section 3: Research Foci Initiatives) and WCRP (Section 3: Grand Challenge on Sea Level Rise and Regional Impacts) priority-related activities.

2.2 Tropical Pacific Observing System (TPOS) 2020

The TOGA-TAO system is experiencing a state of degradation due to funding constraints both from the United States and Japan, the two main supporters of the system. The development of the Argo system is able to replace some aspect of the monitoring of the tropical Pacific Ocean on seasonal to interannual time scales. The international community has been working together toidentify a strategy to design a future Tropical Pacific Observing System that can be best used for monitoring the tropical Pacific to improve the understanding of the coupled ocean-atmosphere system in the Pacific sector, the related prediction of intraseasonal, seasonal, and interannual variability and the decdal and longer modulation, to facilitate biogeochemical applications, and to enhance the direct benefit to the human dimension for 2020 and beyond. Optimal design of the Tropical Pacific of observing system design is an important aspect of the development of TPOS 2020. GSOP will be working closely with the observation, modeling, and assimilation community to identify the best strategy forward for designing TPOS 2020. The GSOP community is already actively involved in the initial discussion of TPOS2020 and contributed significantly to the TPOS2020 workshop that took place in La Jolla, California, USA in January 2014 (http://www.iode.org/index.php?option=com_oe&task=viewEventRecord&eventID=1383). The GSOP community contributed two whitepapers to the workshop on the subjects of ocean state estimation and observing system impact and design. A related task team is being formed under TPOS2020 that closely involves the GSOP community,

2.3 Deep ocean observations

Recent observational and modeling studies have suggested the importance of the deep ocean in ocean heat storage variability and changes on decadal and longer time scales. This has significant implicaitons to global heat and freshwater budgets and climate change research. The current Argo system only reaches 2000-m depth. The development of Argo floats that can reach the full depth of the ocean is an important future direction for global ocean in-situ observations. Due to resources constraints, the development of deep Argo floats need to be strategic and phased. GSOP will work clsoely with the Argo and modeling communities to address the related strategy and expected impacts on ocean state estimation and decadal prediction, including the spatial and temporal sampling and accuracy requirements.

2.4 Ocean Climate Indicators

Climate variability and change have significant societal implications. The oceans, with its vast heat content, play important roles in regulating climate variability and change. Therefore, ocean indicators or indices that reflect climate variability and change have great societal relevance in the same sense as the so-called Keeling Curve, an indicator of CO_2 concentration in the Earth’s atmosphere.

Currently, the ocean and climate research community compute various indices of ocean and climate using resources for individual research projects, often in un-coordinated fashions. A systematic and sustained effort to compute ocean climate indices would benefit not only the general public, but the ocean and climate research community at large by brining a broader and more timely awareness of the ocean's role in climate variability and change.

Much of the existing effort on ocean climate indices has been focusing on global indices such as global upper-ocean heat content and global sea level. However, regional variability and change are often substantially larger than those for global averages. Moreover, regional changes may not be coherent with global average. Well-known examples of these include sea level change in the western tropical Pacific in the past two decades and upper ocean heat content in the South Indian Ocean. Regional changes often have a more direct societal relevance.

Given the above rationales, there is an important need to compute regional ocean indices that can reflect climate variability and change in a systematic coordinated manner using a sustainable approach. Such an effort would benefit the ocean and climate research community as well as the general public. GSOP intends to form an Ocean CLimate Indicator Task Force to create a key list of ocean climate indicators (1) that are important to monitor and understand the variability and change of the physical aspect of the ocean as related to climate, (2) that have important societal relevance, (3) that can be used to evaluate climate models not explicitly constrained by observations, and (4) that can be used to advocate for sustaining and enhancing observing systems.

2.5 Coupled synthesis

Coupled synthesis is being developed at a number of operational centres with the aim of building integrated data assimilation systems suitable for all forms of forecasting from NWP to decadal predictions. Coupled data assimilation is also planned for the next generation of reanalyses. Weakly coupled methods, using the coupled model for forward integration in outer loops, along with separate ocean or atmospheric increment analysis for the inner loop, is a common approach. For example at ECMWF the CERA (Coupled ECMWF ReAnalysis) uses 4Dvar for the atmospheric inner loop and 3Dvar (NEMOvar) for the ocean inner loop, both with a 24hour window, with the atmospheric step applied twice to allow the atmosphere to adjust to the new ocean observations. This has similarities to the coupled DA introduced in Saha et al (2011) at NCEP. Weakly coupled DA should reduce initialisation shocks since the forecasting model is always coupled, but the increments themselves will not necessarily be well adjusted, which would require the development and use of coupled covariances. At ECMWF a weakly coupled reanalysis product is expected to be available within ~3 years.

Keith: Note in particular last sentence. Best if it could have some forward look here?

3 Contribution to the CLIVAR Research Foci and/or WCRP Grand Science Challenges

Consistency between planetary heat balance and ocean heat storage

As described in sections 1.1.6 and 1.1.7 above, the GSOP community has been closely involved in research on surface fluxes and ocean heat budget. GSOP lead the effort to evaluate the consistency of various surface flux products, to improve these products, and to advocate for the enhancement of observations needed to improve flux estimation. GSOP has also significantly contributed to research on ocean heat content, including the potential causes for the recently observed "hiatus" of upper ocean warming (e.g., Carton and Santorelli 2008, Balmaseda et al. 2013). The interaction of GSOP with the climate research community has led to the establishment of the CLIVAR research focus on "Consistency between planetary heat balance and ocean heat storage" and a related working group on "Consistency of Integrated Observing Systems monitoring the energy flows in the Earth System" sponsored by the International Space Science Institute (Bern, Switzerland).

Decadal variability and predictability of ocean and climate variability

Multi-decadal ocean reanalysis products developed by the GSOP community provide a valuable resources to diagnose the nature of decadal and multi-decadal variability in the ocean associated with climate variability. These products have been used to examine the physical processes assocaited with decadal and multi-decadal varaibility, especially for parameters of the ocean that are difficult to be measured directly such as volume and heat transports. (e.g., Wunsch and Heimbach 2006, Shoenefeldt and Schott 2006, Balmaseda et al. 2007, Köhl et al. 2007, Schott et al. 2007 and 2008, Rabe et al. 2008, Köhl and Stammer 2008a). With the continuing improvement of observing systems, ocean models, and assimilation methods, the fidelity of these products in representing decadal variability of the ocean will be further enhanced. The reanalysis products and the assimilation infrastructure provide useful resources to provide feedback tot he observing systems in terms of the observational adequacy and requirement to monitor decadal variability (e.g., Lee et al. 2010). There are also emerging efforts to initialize decadal prediction using ocean reanalysis products (e.g., Pohlmann et al. 2012 and 2013, Belluci et al 2013, Polhmann et al 2014).

Dynamics of regional sea level variability

Ocean reanalysis products developed by the GSOP community have been used to examine the nature of regional and global sea level variability and changes on interannual, decadal, and multi-decadal time scales (e.g., Carton et al. 2005, Wunsch et al. 2007, Köhl and Stammer 2008b). Former and current members of GSOP are actively involved in formulation of the research focus for the dynamics of sea level variability.

Intraseasonal, seasonal and interannual variability and predictability

Ocean reanalysis products developed by the GSOP community are widely used to address intraseasonal, seasonal, and interannual variability of the ocean in relation to climate variability, to evaluate the impacts of observations on constraining seasonal-interannual varaiblity of the ocean, and to initialize seasonal and interannual prediction (e.g., Masina et al. 2004, Capotondi et al. 2006, Köhl et al. 2007, Halkides and Lee 2009, Zhu et al. 2012 and 2013).

Marine biophysical interactions and dynamics of upwelling system

The representation of vertical velocity (thus upwelling) in ocean model is a challenging issue in part because of the lack of direct observaitons and the numerical schemes. The difficulty is exacerbated by some assimilation scheme that may induce spurious vertical motion due to the adjustment to observational constraints that may cause static instability in the water column in assimilation. The GSOP community will be working closely with the research community involved in this research focus by using the observations derived from related efforts to improve the representation of vertical velocity and upwelling in order to provide a more realistic esimtate of the physical state of the ocean that can be used to study biophysical interaction in upwelling systems.

Trends, nonlinearity and extreme events

Ocean reanalysis synthesize diverse sources of observations, including those obtained from different platforms over different periods that may have observational gaps. Therefore, they provide a potentially important resource for the study of trends and their potential effects on extreme events.

ENSO in a changing climate

Due to the relatively long time scales (centennial) of this research focus comparing to the period of modern observations that are used to constrain ocean reanalysis products, GSOP does not have a direct link to research focus.

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